A Polymath in Every Pocket

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In the future, instruction can be generated from portable, reusable objects of great variety. As we move toward this goal, we will be realizing a vision originated more than 50 years go.

Much of what I have to say here is based on a particular view of the future. It is a view that a number of us hold and are building toward, but it is not something that is going to happen tomorrow. I give it 20 years to emerge in a form we envision, and that is probably over-optimistic.

An Outline of the Future

In this future most of what we learn will not come from lessons or other pre-planned, pre-stored didactics but instead from tutorial conversations that are generated in real time and on-demand. These conversations will allow mixed-initiative discussions in which either the tutor or learner can ask questions. They will access something approximating the entire body of human knowledge via some form of today's World Wide Web. They will take place anytime and anywhere the learner wishes.

The conversations will be based on an excruciatingly thorough knowledge of the learner's background, prior knowledge, interests, and preferred learning style(s). They will address exactly what the learner needs and/or wants to know at the moment—"teachable moments" will reign supreme. They will incorporate a full range of multimedia capabilities and employ precisely those instructional strategies that ensure that the learner reliably achieves targeted instructional outcomes. The conversations will be used as much for problem solving (planning vacations and military operations, completing tax returns and operas, repairing radar repeaters and water heaters) as they are for accomplishing the semi-permanent changes in behavior and capabilities sought by education and training.

Because we cannot afford a (human) polymath for every learner or problem solver (e.g., an Aristotle for every Alexander), and certainly not one who is available anytime, anywhere, these conversations must take place using technology—most probably computer technology. The technology will certainly be wireless and voice-interactive, although it will be capable of most other human-computer and computer-computer modes of interaction. It may be hand-held (possibly combined with the game-playing, photograph-taking, instant-messaging, video telephones we have today). It may be worn as an item of clothing (perhaps a shirt). It may even be implanted (although we might set that possibility aside for the moment).

The technological capabilities needed for this future are now within our reach if not our grasp. It is, however, the education, training, and problem-solving functionalities that are going to take the next 20 years or more to develop. Progress has been made, but more is needed. And we will have to wait to see how this future evolves. No doubt the "Columbus Effect" will come into play—we seek the East Indies but end up someplace quite different; we develop wireless telegraph and get radio; we make carriages run without horses and find ourselves on the Santa Monica Freeway. Still I, and some others, view this future as inevitable—absent the end of civilization and the stifling of technological progress.

The real goal, of course, is not technology or even instructional and problem-solving functionalities, but the full and universal realization of each individual's potential. With this goal in mind, those of us laboring in what may be the medieval vineyards of instruction have been working to bring this future about sooner rather than later. The rest of my comments are just to say more specifically what we have been doing based on this view of the future and why.

Motivating Factors

To mention my home base, the Department of Defense (DoD) has been actively working toward this goal with something called the Advanced Distributed Learning (ADL) initiative. This is being done at the request of the White House Office of Science and Technology Policy and in cooperation with the other Federal Agencies. ADL is intended to produce a model for all Federal Agencies to use in making education, training, and performance-aiding readily accessible

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anytime, anywhere. Additionally, however, the DoD has is own stake in ADL.

Among other things, the DoD spends about $17 billion dollars each year on residential schools. These are training schools in specific locations that teach people basic military skills. Of course, Defense training does not end here. Unit training, field exercises, factory training for new systems, sustainment and refresher training, and mission rehearsal must also be conducted. Consideration of these activities would increase the $17 billion figure by a factor of at least three.

Increasing DoD concern in this area is the training and education it provides for its 800,000 or so civilian employees. Also, we might include the K–12 education that the DoD provides for about 90,000 dependent children of military personnel. All together these activities amount to a large, expensive, but operationally essential training and education enterprise, conducted under "one roof," with a major stake in ensuring that the enterprise performs both effectively and efficiently.

A credible argument can be made that well over half the research and development support expended over the last 40 years for instructional technology has come from the DoD. I don't want to argue the specifics of this point here, but I do seek agreement, for the sake of discussion, that DoD investment in this area is both sizable and of national importance—transcending the bounds of military applications and affecting what we do in both civilian education and industry. Both industry and government must rely on the availability of human competence, whenever and wherever it is needed. In this sense, the *anytime, anywhere* vision described earlier is important to us all.

Please note that the efficiency we seek in military and industry education and training is not irrelevant to K–12 education. K–12 students' time is not without value. They have a limited amount of time (it looks like 12 or 13 years here) to identify and then work in a concentrated manner to achieve their potential before other priorities intrude. Any nation with an interest in its own productivity and economic well-being has a major stake in helping them do that efficiently.

But to return to the anytime, anywhere issue, it seems increasingly necessary for individuals and groups of individuals who are no longer in school to find ready access to instruction and performance-aiding. They have to have information when and where they need it, and they have to be prepared for the unexpected. This is especially true in military operations. Plan as we will for an operation, once it is launched, chaos typically ensues—if not chaos, then unexpected exigencies inevitably arise. This situation is not unusual in civilian activities—the inexorable march of science and technology see to that. And to complicate matters, we tend to forget what we've learned in education and training and need help recalling it. Ready access to instruction, problem solving, and decision aids seems to be increasingly important in all sectors.

Enlisting Technology

We might now review some of the arguments that we have been using for 30 years or so to try and convince the DoD of the virtues of technology-based education, training, and performance-aiding. And we might begin with individualization—tailoring interactions to the needs of the learner.

Individualization seems important in K–12 education and is probably more so in adult learning. The difference in learning between students who are tutored one-on-one—one teacher, one student—versus one teacher and 26.5 students (the last reported average size of classrooms) is, as Benjamin Bloom's now-ancient (1984) data suggest, immense. Bloom reported differences in learning between the two approaches amounting to something like two standard deviations. It is not surprising to find that students learn more from tutoring than from classrooms. What was striking in Bloom's research is the size of the difference he and his students found. A two-standard deviation difference is roughly equivalent to raising the achievement of 50th percentile students to that of 98th percentile students. Bloom called it the 2-Sigma challenge.

Overall, individualization comes down to what Michael Scriven described in 1975 as an educational imperative and an economic impossibility. But now, 30 years later, it seems to have become possible. We have affordable technologies that can be used asynchronously, they can be accessed anytime and anywhere, and they can be geared to the specific needs of specific individuals. As I have been suggesting to anyone who would listen (or read) for the last 15 years or so (e.g., Fletcher, 1992), technology allows us to meet Bloom's 2-Sigma challenge at least half-way. Individualization of sequence, content, style, and pace are all now affordable and accessible.

However, in looking at data accumulated over the years, I have become less certain of the ways in which individualization pays off. Individualizing for content, sequence, and context must be worthwhile, but let's consider, all by itself, individualization of pace—allowing individuals to proceed as rapidly as they can or as slowly as they need to in progressing toward targeted instructional objectives.

Anyone who has taught in classrooms knows these differences are large, but, as with tutorial versus classroom instruction, it is surprising to see how large they are. Consider the following differences:

- Ratio of time needed to build words from letters in kindergarten—13:1 (Suppes, 1964).
- Ratios of time needed to learn in grade 5—3:1 and 5:1 (Gettinger, 1984; Gettinger & White, 1980).
- Ratios of time needed by hearing impaired and

Native American students to reach mathematics objectives—4:1 (Suppes, Fletcher, & Zanotti, 1975, 1976).

- Overall ratio of time needed to learn, K–8—5:1 (Carroll, 1970).
- Ratio of time needed by college undergraduates to learn LISP—7:1 (Private communication, Corbett, 1998).

As Tobias (1989) suggested, these differences may mostly be due to prior knowledge, rather than ability—although ability may to some extent beget an urge to learn. Whatever the case, it seems reasonable to conclude, as Carroll did in 1970, that, generally, you will find in a K–8 classroom students who are prepared to learn in one day what it will take other students five days to learn.

Dealing with Differences

How does a human teacher with 26.5 students cope with these differences? Generally, a teacher must focus attention on some students and to some extent leave others to fend for themselves. The result is that in most classrooms some students are lost and others are bored stiff. Individualizing for pace is something that we have been able to do from the very beginning of computer-based instruction (e.g., Suppes & Morningstar, 1972). It may be that our students would receive most of its benefits if we did nothing more than tailor pace to their individual needs.

What about interactivity? Here we might take a serious look at the interactivity technology provides—'interactivity' in this case may be measured as the number of question-answer exchanges. Consider, for instance, the following research data:

- Number of questions a student might answer in an hour of classroom instruction: 3 (Graesser & Person, 1994).
- Average number of questions a student answers in an hour's tutorial session: 120–150 (Graesser & Person, 1994).
- Number of questions a student might answer in an hour of computer-based instruction: 240–480.

The above data on number of questions a student might answer during an hour of classroom instruction is an overestimate. In their review, Graesser and Person (1994) found that teachers asked an average of three questions during an hour of classroom instruction. A student might then answer three questions in an hour if she/he was the only one responding. My own data of 240–480 questions answered in an hour of computer-based instruction is an extrapolation compiled from 15–30 minute daily sessions across a variety of subject matters and instructional approaches. At eight responses a minute, the intensity of interaction could have been too much for some students if the sessions lasted an hour. In any case, the differences in interactivity measured by the number of questions a student must answer, per unit time, are substantial.

We do not have data on how many questions a student may ask in an hour of computer-based instruction. It is likely to be zero in many cases, but it can be many more when mixed-initiative approaches are used. We do have the following two data points:

- Average number of questions a student asks in an hour of classroom instruction: 0.1 (Graesser & Person, 1994).
- Average number of questions a student asks in an hour of one-on-one tutorial instruction: 20–30 (Graesser & Person, 1994).

We could argue about the absolutely correct numbers here, but it seems unlikely that they would differ qualitatively from the above data. Again, the data reveal substantial differences in classroom versus one-on-one tutoring. Individualization and instructional cleverness aside, many of the advantages found for tutorial instruction, whether presented by humans or computers, may be simply due to the large amount of interaction made possible by one-on-one instruction. Under these conditions, we could have really stupid instruction still giving great returns. Overall, simple-minded pacing and interactivity may be accounting for most of the differences we find in comparisons of classroom, one-on-many instruction with tutorial, one-on-one instruction.

Okay, what are some of the differences we find in these comparisons? Here are some data:

- Average effect size from 233 studies comparing achievement under computer-based and classroom instruction: 0.39 standard deviations.
- Average effect size from 47 studies comparing achievement under multimedia computer-based instruction and classroom instruction: 0.50 standard deviations.
- Average effect size from 11 studies comparing achievement under "intelligent tutorial instruction" and classroom instruction: 0.84 standard deviations.

These are my data from evaluations performed over the last 35 years or so. Again, we could argue about the numbers here, but the qualitative results are hard to avoid. This stuff (i.e., technology-based instruction) works. Moreover, as our systems become more sophisticated (from basic computer-based instruction, to computer-based instruction with multimedia, to intelligent tutoring systems), the findings in favor of technology-based instruction increase. Something more than adjustment for pace and increased interactivity may be at work here, but more thorough examination of that issue remains to be determined. For instance, Mayer's discussion of the "Multimedia Principle" (e.g., 2001) does much to explain the impact of multimedia on learning.

Committing

At this point, the effectiveness of technology-based instruction may appear to be genuine, but should we use it? At the heart of every administrative decision concerning new capabilities, however attractive and valuable, lies the question of what we must give up to get them. The issue comes down to cost-effectiveness. Please consider Table 1.

Table 1. Percent time savings for technology-based instruction.

Reference	Number of Studies	Average Time Saved (Percent)
Orlansky & String (1977)	13	54
Fletcher (1997)	8	31
Kulik (1994) (Higher Education)	17	34
Kulik (1994) (Adult Education)	15	24

These data get at the cost issue indirectly. They suggest that in general and roughly that the capabilities (i.e., individualization) provided by technology based instruction produce a 30 percent savings over classroom instruction in the time students need to achieve targeted instructional objectives. Most of these studies treated time savings as an afterthought. I suspect that the magnitude of time savings they report could easily have been increased if the developers of the instruction in these reviews had focused on that outcome.

It may be interesting to consider what the impact on costs might be if outcomes were held constant and time to achieve them were reduced by 30 percent—a possibility that should be of particular interest in military and industrial training circles. We did not have access to industry data, but we could perform this analysis for Specialized Skill Training in the DoD. This is the post-basic training military personnel receive to prepare them for specific military occupations—about 85 percent of which have fairly direct civilian counterparts. It is a subset of all the residential training that the DoD conducts and it costs about $4 billion a year to do so. Here are some results from this analysis:

- Amount saved by reducing by 30 percent the time needed to train 20 percent of Specialized Training students: $263 million.
- Amount saved by reducing by 30 percent the time needed to train 40 percent of Specialized Training students: $525 million.
- Amount saved by reducing by 30 percent the time needed to train 60 percent of Specialized Training students: $789 million.
- Amount saved by reducing by 30 percent the time needed to train 80 percent of Specialized Training students: $1,051 million.

The analysis suggested a monotonically increasing linear model of savings that might well change shape with more examination, but it is conservative and does not consider such possibilities as using technology to reduce travel and temporary duty-station costs through the use of anytime, anywhere technology.

For that matter, the 30 percent figure itself conservatively estimates the amount of training time that actually can be saved. Many Defense training contractors gamble on being able to reduce time to train by 50 percent through, among other things, the use of technology. Time savings as great as 80 percent have been reported (Noja, 1991). The analysis is also conservative in only considering time and not including the substitution of simulated for actual equipment. Anytime you can substitute a $2,500 computer for equipment costing tens, hundreds, or even hundreds of thousands of dollars, you save considerable amounts of money.

Finally, this analysis considers cost alone. If we wish to select among a variety of alternative approaches, we may want cost-effectiveness analyses. Performing these analyses usually requires that you either hold costs constant and look for maximized effectiveness, or hold effectiveness constant and look for minimized costs to produce it. Moreover, you have to do this across a variety of approaches. Although we say it all the time, it is just not correct to call some approach 'cost-effective.' We have to say cost-effective compared to *what.*

There are good DoD data that address this issue by comparing the costs of simulator based training with the costs of using actual equipment, but I suspect that folks outside the military are more interested in education issues. Fortunately, and with a little help from some colleagues in K–12 education, we were able to perform a cost-effectiveness analysis concerning ways to increase mathematical achievement by one standard deviated as measured by scores on a standard test. Data from this work are presented in Table 2.

The results in Table 2 favor computers in classrooms, but it is notable that this alternative is not incompatible with peer tutoring—both could be used together if two or more students work together. We don't have cost data on this approach, but the effectiveness data, both ancient and recent, suggest favorable results (e.g., Grubb, 1964; Shlechter, 1990).

The 'Rule of Thirds'

In sum and across all these studies, a 'Rule of Thirds' seems to emerge. Technology-based instruction

Table 2. Costs (constant 1997 dollars) to raise mathematics scores by one standard deviation (adapted from Fletcher, 2003).

Instructional Alternative	Annual Costs
Tutoring (20 Min./Day):	
Peer Tutors	$427
Adult Tutors	2404
Reduce Class Size from:	
35 to 30	1466
35 to 20	2039
Increase Instruction Time 30 Min./Day	3977
Microcomputers in Classrooms	
Grade 3	286
Grade 5	307

reduces the costs of instruction—infrastructure costs—by about a third. Additionally, you can either hold objectives constant and reduce the time to achieve them by a third, or you can hold time constant and increase achievement by about a third. The 'Rule of Thirds' is, per usual practice, conservative in light of what may actually be possible through the use of technology.

Of course, for industry and for the DoD, the real payoff is not just improved personnel effectiveness, competence, and productivity, but also what they yield in improved organizational effectiveness, competence, and productivity.

The above comments address the analog of what might, in economic terms, be called training supply. Instead of enhancing training supply, can we reduce training demand? We can actually do both, but let's look at reducing training demand through the use of technology-based performance aids. They could also be described as decision aids, job aids, or just 'tools.' We have some cost and effectiveness data concerning these.

For instance, we (Fletcher & Johnston, 2002) reviewed evaluations of a number of technology-based, anytime, anywhere performance aiding systems. Perhaps the best and most complete evidence is provided by assessments of the Integrated Maintenance Information System (IMIS).

IMIS is a wearable computer-based device for providing performance-aiding to avionics maintenance technicians. Thomas (1995) compared the performance of 12 Avionics Specialists and 12 Airplane General (APG) Technicians on 12 fault isolation problems concerning three F-16 avionics subsystems—the fire control radar, heads-up display, and inertial navigation system. Training for APG Technicians covers very general aspects of aircraft maintenance, only a small portion of which concerns avionics. In contrast, Avionics Specialists must meet higher selection standards and receive 16 weeks of specialized, more expensive, training focused on avionics maintenance.

Within each of the two groups of subjects, six of the fault isolation problems were performed using paper-based Technical Orders (Air Force technical manuals) and six were performed using IMIS. The results are shown in Table 3.

Table 3. Maintenance performance of 12 Air Force avionics specialists and 12 general (APG) technicians using technical orders (TOs) and IMIS (from Fletcher & Johnston, 2002).

Technicians/ Performers	Correct Solutions (Percent)		Time to Solution (Minutes)		Average Number of Parts Used		Time to Order Parts (Minutes)	
	TOs	IMIS	TOs	IMIS	TOs	IMIS	TOs	IMIS
Avionics Specialists	81.9	100.0	149.3	123.6	8.7	6.4	19.4	1.2
APG Technicians	69.4	98.6	175.8	124.0	8.3	5.3	25.3	1.5

As suggested by the table, when either the Avionics Specialists or the APG technicians used technology-based IMIS rather than paper-based Technical Orders, they found more correct solutions in less time, used fewer parts to do so, and took less time to order them. When the performance of APG Technicians using IMIS was compared with that of Avionics Specialists using Technical Orders, they found more correct solutions in less time, used fewer parts to do so, and took less time to order them than did Avionics Specialists. Finally, when the APG Technicians using IMIS were compared with Avionics Specialists using IMIS, they performed just about as well as the Avionics specialists, and even slightly better in the number of parts used.

The economic promise suggested by these results could well vanish if the costs to provide the performance aid (IMIS) exceed the costs they otherwise save. Teitelbaum and Orlansky (1996) were able to estimate reductions in depot-level maintenance, organizational-level maintenance, and maintenance and transportation of inventories of spare parts. After considering the costs to develop and maintain IMIS, they reported about $20 million per year in net savings for the full fleet of Air Force F-16s. Notably, these savings arise only from applying IMIS to three avionics subsystems. Moreover, the savings do not include reduced costs for: (a) selection and training from eased requirements to recruit and train specialized personnel; (b) training from using IMIS as both a performance aid and a training device; and (c) printing, distributing, and, especially, updating paper technical manuals. Most importantly, costs savings disregard the significant benefits arising from increased flight sortie rates and enhanced operational effectiveness resulting from the improved performance of maintenance personnel.

A Revolution?

In sum, the above results suggest that these technology-based approaches are effective, that we can bundle training with performance-aiding, that we can deliver both anytime, anywhere, and that good arguments can be made for their cost reductions and cost-effectiveness compared with other approaches.

In effect we may be seeing a major revolution in learning. Several thousand years ago, writing made the content of learning available anytime, anywhere, and a few hundred years ago, books made that content more accessible and affordable. But technology does something more: It allows both the content and tutorial interaction with the content to be available anytime, anywhere. This notion underlies the establishment by the DoD of the Advanced Distributed Learning (ADL) initiative, and it returns us to the vision of the future I mentioned at the beginning of these comments.

Even if learning and performance-aiding conversations are going to be created in real-time and on demand, they must start with something—especially if they are going to access a full range of existing human knowledge. What will they draw from the global information grid, or whatever the World Wide Web becomes in the future? What features must these elements possess to support these conversations? In the ADL initiative we have tried to address these issues. We decided that the conversations we envision will be object-oriented—built from objects of some sort, found somewhere.

The Object Economy

We decided that the future would be based on what Spohrer, Sumner, and Shum (1998) have called an "educational object economy." In such an economy, the emphasis in preparing materials for instruction or performance-aiding shifts from the current concern with developing instructional objects themselves to one of integrating already available objects into meaningful, relevant, and effective interactions. Gibbons, Nelson, and Richards (2000) reviewed in detail the nature and value of instructional objects for educational applications and concluded that they may be the technology of choice in supporting the evolution of technology-based instruction because of their potential for reusability, adaptability, and scalability. Instructional objects may then supply the primitives from which instructional and performance-aiding interactions can be created on-demand and in real-time.

These objects may take a variety of forms expressed in a variety of media, but in accord with Gibbons *et al.*, we decided that they must be accessible, portable, durable, and reusable. That is to say, we assumed: that it must be possible to find and retrieve the objects, that they must be able to operate in most computing environments and on most platforms, that they will continue to operate despite changes (modifications, updates, and revisions) in the base environment, and that they can be used over and over in multiple applications.

These considerations became criteria for the objects from which we assume real-time, on-demand learning and performance-aiding conversations can be built and sustained. Hence, our development of SCORM, the Sharable Content Object Reference Model. SCORM attempts to define the interrelationship of components, data models, and protocols so that they may be shared across systems that conform with the same model. It does not specify any particular platform, operating system, application language, or even instructional strategy. It relies on what might be called virtual interfaces to ensure that, whatever the objects do, they can be incorporated into an ongoing presentation—or conversation.

SCORM was created by assembling elements (metadata, programming interfaces, data models, etc.) mostly developed and found elsewhere. It was intended to orchestrate and draw as much as possible on what others in the learning and performance-aiding community wanted to do anyway. Its development required considerable involvement from industry, whose participants had to set aside their competition for market share in order to create common specifications that would increase the size of the education, training, and performance-aiding market. Everyone shared in the long-term vision of developing sharable content objects that we could use to provide learning and assistance anytime, anywhere.

SCORM now includes specifications for object aggregation, run-time environments, data sharing, and sequencing. It appears to be stabilized and ready for use in creating education, training, and performance-aiding. How flexible it is and the extent to which it can support sophisticated instructional capabilities, such as the intelligent capabilities needed to support our long-term vision of learning conversations, remain to be determined. Modifications and updates will no doubt be needed, but the present version of SCORM has received wide acceptance. Its specifications are being adopted across Europe, Asia, the Pacific Rim, and the Americas. It appears that more than four million objects that observe the SCORM specifications now exist and are in use.

Next Steps

A next step on a different but related dimension is represented by CORDRA, the Content Object Repository, Discovery, and Resolution Architecture. It is yet another reference model, this one focused on identifying ("discovering") and then finding precisely the content that's needed for some application. Like available search engines, CORDRA will rely on metadata to specify and locate content, but its registries will make it possible to identify and locate content that is not just available from the Internet, but also held anywhere in any registered repository. It will identify the content we seek with far greater precision than the thousands of hits we typically receive from text-based search engines, and it will keep track of content as it is modified and moved from repository to repository. Like SCORM, CORDRA will, as much as possible, be built on existing standards and specifications, which mostly need to be orchestrated and combined to achieve the necessary sharability, and interoperability.*

Basically, we assume that the future we envision will arise from four main technical opportunities: advances in electronics, the pervasive accessibility of the World Wide Web, emerging specifications for reusable, sharable instructional objects, and the development of intelligent tutoring systems (ITS). The first three seem inexorable and practically inevitable. ITS may deserve a few comments.

At this point, it may be worth emphasizing the capabilities provided by "non-intelligent" computer-based instruction since the 1950s. They have been able to:

- accommodate individual students' rate of progress, allowing as much or as little time as each student needs to reach instructional objectives;
- tailor both the content and the sequence of instructional content to each student's needs;
- make the instruction as easy or difficult, specific or abstract, applied or theoretical as necessary; and
- adjust to students' most efficient learning styles (collaborative or individual, verbal or visual, etc.).

These capabilities have been described, discussed, and reviewed by many commentators since the 1950s (e.g., Coulson, 1962; Galanter, 1959). To one degree or another, they have been implemented and available in computer-based instruction from its inception. However, 'intelligence' in intelligent tutoring systems is a different matter.

Intelligence

When intelligence was first introduced into computer-based instruction it concerned quite specific goals. The distinction between ITS and other computer-based instruction was keyed to these goals and specific capabilities that were first targeted in the 1960s (Carbonell, 1970; Sleeman & Brown, 1982). Two of these defining capabilities are that intelligent tutoring systems:

- allow either the system or the student to ask open-ended questions and initiate instructional, "mixed-initiative" dialogue as needed or desired; and
- generate instructional material and interactions on demand rather than requiring developers to foresee and pre-store all such materials and interactions needed to meet all possible eventualities.

Mixed-initiative dialogue requires for conversation a language that is shared by both the system and the student/user. Although formal languages have been used in ITS, natural language has been a frequent choice for this capability (e.g., Brown, Burton, & DeKleer, 1982; Graesser, Person, & Magliano, 1995). Progress continues to be made in dialogues based on natural language (Graesser, Gernsbacher, & Goldman, 2003).

Generativity

Generative capability requires the system to devise on demand—not draw from predicted and pre-stored formats—interactions with students. This capability involves not just generating problems tailored to each student's needs, but also coaching, hints, critiques of completed solutions, appropriate and effective teaching strategies, and, overall, the interactions and presentations needed for one-on-one tutorial instruction. These interactions must be generated from information primitives using an "instructional grammar" that is analogous to the deep structure grammar of linguistics.

The generative capability sought by ITS developers is not merely something nice to have, but essential if we are to advance beyond the constraints of the prescribed, pre-branched, programmed learning, and *ad-hoc* principles commonly used to design computer-based instruction. We need an interactive, generative capability if we are to deal successfully with the extent, variety, and mutability of human cognition. We especially need it to realize the future we envision. As with natural-language dialogue, progress has been made, but more is needed. Still, even though the ITS goals remain beyond the current state of the art, they are not beyond our horizons.

So where might all this lead? What if we are amazingly successful and actually begin to deliver education, training, and performance-aiding as on-demand conversations delivered in real-time anywhere and anytime? Here are a few possibilities:

No pre-defined sequencing. These conversations will take whatever direction is needed by those involved in them. Sequences will be adjusted on the fly

*CORDRA is under development and evolving, but one place to find out more about it is: *http://cordra.lsal.cmu.edu;* information about both SCORM and CORDRA can be found at *http://www.adlnet.org* as needed. The notion of instructional design as a process of pre-specifying and pre-defining a sequence of activities within a lesson module will be largely replaced.

No tests. Well, much less reliance on explicit tests to determine progress toward learning or problem-solving objectives. They will be replaced by unobtrusive, continuous assessments intended to develop an evolving model of the learner/user from interactions with the system. These assessments may take account of the learner's vocabulary, use of technical information, level of abstraction, clustering (chunking) of concepts, inferred hypothesis formation, and the like. Some explicit testing and explicit probing may still be used to assess learner progress efficiently, but what sort of tests will be needed, how they are implemented, and what principles will guide their psychometric properties remain to be determined.

No lessons. The notion of monolithic instructional modules intended to achieve instructional objectives may certainly change if learning and performance-aiding take place as real-time, on-demand conversations. Objectives will remain along with the need to track progress toward achieving them, but how that is done will change as the objectives themselves become more varied and negotiable.

Conclusion

In conclusion, it might be noted that the title heading all these comments is probably wrong. It is one thing, perhaps a necessary thing, to have a polymath at hand (or in the pocket), especially one with ready accesses to most, if not all, human knowledge. However, we've all met very knowledgeable people who are poor teachers and mentors. In addition to world knowledge, the conversations we envision depend on effective instructional and performance-aiding strategies, accurate representations of the user, and comprehensive, focused identification of relevant subject matter. Systems of this sort have been the objective of research and development investment since the mid-1960s (Carbonell, 1970). Generative capabilities in these systems remain essential to realizing the future envisioned here. The development of instructional objects takes us closer to achieving these goals.

The anytime, anywhere objectives of the future discussed here are not contrary to classroom instruction, but very different. The envisioned conversations will be able to accomplish many things beyond the reach of any human tutor, but they will still be computer-based. Bits and bytes 'think' differently than human brains, and humans will still be needed to do things only humans can do.

However, this future will require changes in roles and responsibilities of students, instructors, and administrators. Organizational structures and the roles of instructional institutions now focused on classrooms will also require major modifications when education, training, and performance-aiding become ubiquitous and fully accessible. Like all changes, these are likely to be painful and most certainly difficult to achieve. However, enabling the totality of human knowledge to be affordable and available to every individual who seeks it seems a worthy goal. We may well wish that both the technical and administrative difficulties encountered in realizing this vision can and will be surmounted. □

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The Interplay of Learning Objects and Design Architectures

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The computational problem of learning objects is the rapid, automated design and assembly of adaptive instructional experiences. It is therefore a problem about the architectures that contribute to creating such experiences. Though the problem of learning objects may seem to be a simple matter of determining how to find objects and sequence them, instructionally it is a problem of the *instantaneous computational design of a conversation.*

The Challenge: Instructional Design

Today, those who are attempting to turn learning objects into a viable and stable technology face major challenges. The most difficult of these will arise during the *conception* of designs and not during their *execution.* The instructional design aspect of learning objects will present more complex puzzles than the software implementation aspect. My goal is to describe the architectural challenge of making learning objects a

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